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Modified sliding mode design of passive viscous fluid control systems for nonlinear structures

A.R. Zare, M. Ahmadizadeh*

Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

A strategy is developed for design of passive control systems for structures experiencing inelastic deformations during earthquake loading. Besides the addition of passive energy dissipation devices, the proposed method suggests the required changes to the stiffness and strength of the structure, to reduce the absolute acceleration and relative deformation responses simultaneously. For this purpose, the locations and amounts of modifications in stiffness, strength and damping are determined by a sliding mode control algorithm to consider the nonlinear behavior of the structure. Being originally designed for active control, the sliding mode algorithm is modified to facilitate the extraction of the optimum properties of the passive control system from the active control design. By considering nonlinear structural response in design, the proposed technique provides a means for proper design of control systems to achieve the desired performance goals in major seismic events. Furthermore, by taking advantage of the freedom to simultaneously modify the structural stiffness, strength and damping properties, the proposed design method provides more versatility in the achievement of these performance goals. The effectiveness of this development is demonstrated through the analysis and design of control systems for an eight-story structure.

1. Introduction

Active, hybrid and passive control of civil engineering structures have been proven to be effective methods to enhance their resistance to extreme environmental loads [1,2]. The control systems are often designed to reduce the structural response and demands to amounts bearable by structural elements. To this end, inter-story drifts have been the primary center of attention in design of such systems in most design methods. In contrast, a number of studies [3–5] have demonstrated that in addition to the inter-story drifts, the absolute acceleration response needs to be controlled for safety, integrity and serviceability of buildings [1,6,7]. While structural failure occurs when deformation of a story or an element exceeds a certain ultimate limit, the failure of secondary or nonstructural components may be a direct result of excessive absolute acceleration at certain locations of the structure [6,8]. Sensitive equipment in hospitals and communication centers, partition walls, furniture, ventilation and air conditioning systems are examples of such acceleration-sensitive components. Furthermore, large absolute accelerations may reduce human comfort at serviceability limit states [3,8].

Compared to active and hybrid control devices, passive dissipation devices are more prevalent [9] mainly due to their inherent stability, independence from external power sources, lower cost, and ease of use and maintenance. More recently, it has also been shown that the performance of passive control systems (specifically viscous fluid damping systems) are usually less sensitive to changes in structural properties due to nonlinearity or errors in modeling and estimation [10]. These desirable properties are backed by extensive research to develop advanced design techniques for design of passive control systems [3,11–15]. On the other hand, the improvement of structural performance resulting from the more versatile active control systems is generally better than those of their equivalent passive systems [3]. Furthermore, active control systems can be designed to reduce the absolute acceleration response [1], while a number of passive control systems may inherently increase the absolute accelerations. Examples of such passive systems include hysteretic control systems that may increase the seismic demands due to increased natural frequency, and viscous fluid dampers designed without considering the effects of brace flexibility [3].

To help reduce the acceleration response of structures controlled using passive energy dissipation devices, modification of structural stiffness and strength has received close attention in recent years [3–5,7,16]. Generally, a reduction of stiffness reduces the demands in most seismic regions, and a reduction in strength can reduce the

* Corresponding author.
E-mail address: ahmadizadeh@sharif.edu (M. Ahmadizadeh).

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maximum absolute acceleration response [3]. This usually entails modifications of a number of elements or connections in the lateral load resisting system of the structure, which is only viable if the capacity of the system to withstand other loads is not adversely affected. Negative stiffness devices have also been used for this purpose in the form of pre-compressed springs [16]. In any case, a reduction in lateral stiffness or strength usually leads to increased displacement demands, which can be reverted by adding supplemental damping devices [3–5,7,17,18].

The suitable amounts of softening, weakening and damping in passively controlled multi-degree-of-freedom (MDF) systems can be determined by an iterative approach such as that offered by Lavan [18]. However, active control algorithms are shown to provide a more educated means of determining the required changes in dynamic properties of structures [3,19–21]. In the latter approach, an active control system is first designed for the structure in question, and then a passive control system is designed in such a way that the resulting response is as close as possible to the response of the actively controlled system. One method to make this transition is mimicking the actively-controlled response by iteratively minimizing the difference between the active and passive control force histories for the design earthquakes [4,19]. Alternatively, an equivalent passive control system can be designed by observing the changes made to structural properties by the active control system [3]. This study uses the latter approach, since it provides more control over structural properties and helps better understand the strengths and weaknesses of the passive control compared to its active counterpart. This approach has already been established for a number of linear active control algorithms, such as Linear Quadratic Regulator [17], Pole Assignment [3] and H_2 and H_∞ [21].

This study presents a comprehensive design methodology for design of passive viscous fluid control systems for nonlinear structures using a modified sliding mode algorithm. The main improvements over the existing methods include consideration of nonlinear behavior in design of active control system, simultaneous consideration of displacement and acceleration response in design utilizing modification of damping, stiffness and strength, and use of a non-iterative and technically understandable transition method from active to passive control. The choices made in the proposed design method are supported by a set of parametric studies considering the effects of nonlinear behavior, initial stiffness and damping, and brace flexibility.

Consideration of nonlinear behavior is important in design of control systems that are expected to satisfy certain performance goals in strong excitations, where nonlinear behavior is inevitable and is known to significantly affect the design [11,12]. Both displacement and absolute acceleration response are considered in design to obtain the desired or optimum structural performance. Compared to earlier studies [19,22], the tedious "optimization" iterations are avoided in transitioning from active to passive control. This is achieved by modifying the control algorithm in such a way that the properties needed in design of the passive control system can be extracted directly from the properties of the actively controlled system. In addition to being simpler and less computationally expensive, this approach helps the designer to observe the required changes in the dynamic properties of the system to achieve the actively-controlled response, and then select and apply the most effective changes that can be attained merely using passive control devices along with stiffness and strength modification. Furthermore, implementing a passive control system that is better designed for nonlinear structures leads to more economical design of the control system and the structure itself.

Following the introduction of this methodology, an example structure is designed using this approach. The performance results are then compared to those of control designs using other well-established methods to demonstrate the effectiveness of the technique presented in this study.

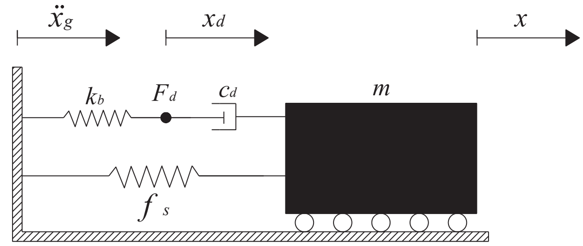

Fig. 1. SDF system with a viscous damping devices connected using a flexible brace.

2. Effects of weakening, softening and damping

Simultaneous reduction of absolute acceleration and inter-story drifts in passively controlled systems can be achieved by the means of weakening, softening and passive damping [3–7,19,20,22]. A set of brief parametric studies is carried out in this section to provide a critical evaluation the effectiveness of each parameter in the design of a passively controlled system. Consider a single-degree-of-freedom (SDF) system equipped with a viscous fluid damper that is connected through a flexible brace as shown in Fig. 1.

In this figure, f_s is the nonlinear restoring force of the spring, m represents the mass of the system, k_b is the stiffness of the brace and c_d is the linear damping coefficient of the control device. For simplicity, the inherent damping of the system is ignored.

The equation of the motion for the SDF system can be written as:

$$\ddot{x}_t(t) = \ddot{x}(t) + \ddot{x}_g(t) = \frac{-f_s(t) - F_d(t)}{m} \tag{1}$$

where $\ddot{x}_t$ is total acceleration of the mass, $\dot{x}$ and $\ddot{x}$ are the relative velocity and acceleration, respectively, and F_d is the force of the spring-dashpot model, which can be obtained from:

$$F_d(t) = k_b x_d(t) = c_d[\dot{x}(t) - \dot{x}_d(t)] \tag{2}$$

To simplify the parameters involved in analysis, first the initial natural period of the system is defined as $T_{n0} = 2\pi(m/k_0)^{0.5}$, where k_0 is the initial spring stiffness. A relation is also established between the initial spring and brace stiffness using a positive proportionality constant a^2 as:

$$k_b = a^2 k_0 \tag{3}$$

Furthermore, the damping coefficient c_d in Eq. (2) is replaced with the following expression:

$$c_d = \frac{4\pi\xi m}{T_{n0}} \tag{4}$$

wherein a dimensionless parameter ξ is introduced as a measure of the damping ratio of the system. It should be noted that this parameter is different from the true equivalent viscous damping ratio of the system due to brace flexibility. Finally, as a measure of nonlinearity of the response, a ductility based reduction factor is employed in the parametric analyses defined as:

$$R_\mu = \frac{f_{sL}}{f_{sN}} \tag{5}$$

In this equation, f_{sL} and f_{sN} are the maximum restoring force of the linear and yielding force of the nonlinear systems (term f_s in Eq. (1)), respectively.

The ranges of the above-mentioned parameters considered in the analyses are listed in Table 1. The responses of the resulting more than 10,000 models are simulated using the Northridge earthquake excitation record (M 6.7, Arleta-Nordhoff Fire Station, 0.344 g PGA).

The peak drift and absolute acceleration responses are averaged and plotted in Figs. 2 and 3. Each data point of each graph is obtained by averaging the analysis results corresponding to the value shown on the